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Evaluation of Gamma Ray Attenuation for Measuring Soil Bulk Density Part II. Field Investigation

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Abstract

A field investigation was conducted at sites near Lexington and Central City, Kentucky, to evaluate the use of gamma ray attenuation for measuring soil bulk density. Experiments were conducted whereby the gamma gauge was calibrated by various means and compared with volumetric cores collected from the field soils. Calibration by the manufacturer's recommended procedure was determined to be as accurate as more rigorous laboratory calibration or calibration via regression of soil bulk density data, provided that the effect of soil water on gamma attenuation is correctly considered. We also developed a linear regression equation to correct for the occurrence of deviation from prescribed separation distance between the gamma source and detector [254 mm (10 in.)]. Experiments indicated that soil moisture content and soil depth had no effect on the accuracy of determination of dry soil bulk density by the gamma gauge. **Keywords.** Soil, Bulk density, Gamma ray attenuation, Gamma density gauge.

Introduction

The ability to measure soil bulk density in the field is of vital importance in studies of vehicle soil compaction and tillage operations. Erbach (1988) has presented an extensive review of methods used to measure soil bulk density *in situ*. He cited the relative ease of using gamma attenuation versus collection of volumetric cores but indicates an uncertainty of 0.03-0.5 $Mg{\cdot}m^{-3}$ associated with gamma density measurements. Steele et al. (1983) concluded that gamma gauge measurements did not adequately agree with volumetric core determinations unless empirically calibrated for the specific soil conditions being investigated .

Characterization of field soil conditions generally requires multiple determinations of physical parameters in order to account for spatial variation. The relative ease of measuring soil bulk density using a gamma gauge versus collection of volumetric core samples thus becomes more important in field studies. Also, the dual probe gamma gauge can be used to monitor changes in soil density at a specific location over time. However, these advantages are of little value unless the accuracy of gamma soil density measurements can be assured.

In a companion laboratory study (Luo and Wells, 1992), we showed that gamma ray attenuation could be accurately used to measure soil bulk density in clay loam, silt loam, and sandy loam soils. We confirmed the findings of previous researchers that: a) the attenuation characteristics of soil material are significantly different from that of water; and b) gamma ray attenuation by soil is independent of soil texture or type. We further determined that a relatively simple procedure could be used to calibrate the gamma gauge, provided that the influence of water on attenuation was properly considered. It thus remained to evaluate these procedures in the determination of bulk density in field soils.

The objectives of this study were to:

- Determine if a dual probe gamma density gauge could be used to accurately measure *in situ* soil bulk density as determined from volumetric cores collected from field soil profiles.
- Identify the calibration procedure necessary to achieve accurate measurement of soil bulk density.
- Define a relationship whereby correction can be made for inaccurate spacing between gamma source and detector in the determination of soil bulk density.

Background

The attenuation of monoenergetic gamma photons is dependent upon the number of electrons situated between the source of gamma photons and a detector. Part I of this study (Luo and Wells, 1992) describes how soil dry bulk density can be expressed in terms of the measurements of gamma ray attenuation as follows:

$$D_{ds} = (ln(I_o) - ln(I))(x\,\mu_s + x\,\mu_w\,\theta_m)^{-1} \qquad (1)$$

where

D_{ds} = dry bulk density of soil ($Mg{\cdot}m^{-3}$),
I = number of gamma photons passing from source to detector through a soil mass per unit time (counts/minute),
I_o = unattenuated count rate (through air) for the source (counts/minute),

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x = soil thickness or distance between the source and detector (mm),
μ_s = mass attenuation coefficient for soil ($m^2 \cdot Mg^{-1}$),
μ_w = mass attenuation coefficient for water ($m^2 \cdot Mg^{-1}$), and
θ_m = gravimetric (dry basis) soil moisture content (dec.).

Manufacturers of gamma density gauges typically utilize a relationship such as:

$$D_{ws} = \frac{\left(ln\left(\frac{A}{CR}\right)\right)}{B} \tag{2}$$

where
D_{ws} = wet soil bulk density ($Mg \cdot m^{-3}$),
CR = a count ratio (I/I_r),
I = gamma count through soil (counts/min),
I_r = count through a reference material of known density (counts/min), and
A, B = regression coefficients.

The coefficients A and B are determined by taking count rates in various materials of known bulk density. This calibration procedure is recommended periodically to verify instrument accuracy. A "field" calibration generally consists of daily determination of the count rate (I_r) through a reference material.

Dry soil bulk density, D_{ds} ($Mg \cdot m^{-3}$), can be determined from wet bulk density, D_{ws}, using the following equation

$$D_{ds} = \frac{D_{ws}}{1 + C_2\, \theta_m} \tag{3}$$

where C_2 is the ratio of the average soil mass attenuation coefficient to that of water. We determined this ratio to be approximately 0.8965 (Luo and Wells, 1992). Thus, equations 2 and 3 can be used to determine dry soil bulk density by means of a gamma count rate and gravimetrically determined soil moisture content.

Steele et al. (1983) suggested that acceptable agreement between gamma gauge and volumetric core determinations of soil bulk density required calibration of the gauge within a specific soil condition. They used a quadratic function of count ratio and determined regression coefficients via comparison of gamma and core bulk densities. They found these coefficients to hold only for the specific soil conditions for which they were determined.

Instead of an empirical calibration relationship expressing wet bulk density as a function of count ratio (CR), we (Luo and Wells, 1992) defined an empirical or regression calibration factor which is a linear function of soil water content:

$$D_{ds} = (C_3 + C_4\, \theta_m)\, D_{ws} \tag{4}$$

where C_3 and C_4 are regression coefficients. This required the determination of soil bulk density by means of volumetric core samples and also determining corresponding gamma counts. The coefficients, C_3 and C_4, were thus determined as best fit values of equation 4 for a specific soil type with D_{ws} determined by equation 2 as before.

Finally, in part I of this study (Luo and Wells, 1992) we proposed a relatively simple linear relationship for the purpose of correcting for deviation from the prescribed distance between gamma source and detector which is:

$$D_{ds} - D^*_{ds} = C_5 + C_6(x_s - x^*_s) \tag{5}$$

where
D_{ds} = apparent dry soil bulk density ($Mg \cdot m^{-3}$),
D^*_{ds} = dry soil bulk density corresponding to the correct source/detector spacing ($Mg \cdot m^{-3}$),
x_s = source/detector spacing corresponding to D_{ds} (cm),
x^*_s = correct or prescribed source/detector spacing (cm), and
C_5, C_6 = regression coefficients.

Rationale for the linear form of equation 5 is given in a companion paper (Luo and Wells, 1992). Using data collected from a silt loam soil we determined a correlation coefficient (R^2) of 0.997. It remained for this study to determine whether or not equation 5 can be used to correct for deviation from prescribed source/detector spacing in the field.

Experimental Procedure

Field Sites

Soil bulk density was measured *in situ* at two locations. One site was on an experimental plot associated with a reconstructed soil profile located near Central City, Kentucky. The soil, a Sadler silt loam, was reconstructed on the River Queen surface coal mine of the Peabody Coal Company. The soil consisted of approximately 660 mm (26 in.) of subsoil material placed by large scrapers and approximately 200 mm (8 in.) of topsoil material.

This site was originally constructed to determine the potential effects of deep tillage and various deep rooting plant species in ameliorating subsoil compaction caused by equipment used in soil reconstruction. Quadruplicate test plots of the following treatments were constructed: 1) soil ripped to a depth of 700 cm (28 in.); 2) soil planted in alfalfa for 2 years; 3) soil planted in black locust for 2 years; and 4) soil with no amelioration treatment. Soil bulk density was measured at one location in each test plot at depths of 203, 483, and 710 mm (8, 19, and 28 in.) using both a dual probe gamma density gauge and via extraction of volumetric soil samples.

Measurements were also made in a natural Maury silt loam profile located at Lexington, Kentucky. This soil is characterized by an A horizon approximately 250 mm (10 in.) deep and a B horizon extending to an approximate depth of 1 m (39 in.). Four locations were selected and both gamma gauge and volumetric core bulk density measurements were made at depths of 102, 203, 305, 406, and 508 mm. (4, 8, 12, 16, and 20 in.).

Equipment

A Troxler dual probe gamma density gauge was used in this study. The unit utilized a radioactive source of 5 mCi of Cs 137 which emitted gamma photons at an energy level of 662 KeV. Use of the gauge required placement of two parallel vertical access holes in the soil profile encased with 51 mm (2 in.) diameter aluminum pipe on 305 mm (12 in.) centers. The radioactive source and a detector tube were positioned at the same depths within the respective access tubes and a count was recorded of gamma photons reaching the detector.

Cylindrical soil samples were collected and gamma density gauge readings obtained at selected depths within each soil profile. At the Central City site samples were collected by means of a Giddings hydraulic soil coring device. Two 51 mm (2 in.) holes were placed in the profile on approximately 305 mm (12 in.) centers. Cylindrical samples, 33 mm (1.3 in.) in diameter by 102 mm (4 in.) long were extracted from the core holes at nominal depths of 203, 483, and 710 mm (8, 19, and 28 in.). The samples were encased in polyvinylchloride tubing with an approximate outside diameter of 41 mm (1.61 in.). A special sampling device was constructed for use with the Giddings sampler. The bulk density of each sample was determined by dividing soil dry weight by known sample volume and average moisture content was also determined for each core sample. Gamma density gauge readings were taken at depths of 203, 483, and 710 mm (8, 19, and 28 in.) between the parallel 51 mm (2 in.) diameter holes.

Soil core holes and volumetric samples were obtained manually at the Lexington site. The procedure was different in that the parallel vertical access holes were installed via removing 51 mm (2 in.) diameter soil cores. Gamma density gauge readings were obtained at depths of 102, 203, 305, 406, and 508 mm (4, 8, 12, 16, and 20 in.). Cylindrical samples [54 mm (2 in.) dia., 102 mm (4 in.) deep] were extracted midway between the access holes at each depth for determination of bulk density and moisture content after the completion of gamma measurements.

A special array of vertical access tubes was installed in the soil profile at the Lexington site. In this array the spacing between access tubes (inside-to-inside) was varied between approximately 200 and 300 mm (7.9 and 11.8 in.). Gamma counts were recorded at seven spacings within this range to determine the sensitivity of computed soil bulk density to source-detector spacing.

Gamma Gauge Calibration

Three methods of calibrating the gamma gauge were evaluated in this study. The most rigorous method utilized equation 1 where the parameters I_o, μ_s, and μ_w were determined experimentally for the particular gauge and soils used in this study. Determination of these parameters on a case-by-case basis would be the most theoretically appropriate means of calibrating a particular gauge. We therefore designated this procedure as the theoretical calibration (TC) method. We determined the values of I_o, μ_s, and μ_w to be 178,937 counts/min, 5.63 $m^2 \cdot Mg^{-1}$ and 6.28 $m^2 \cdot Mg^{-1}$, respectively, in a companion study (Luo and Wells, 1992).

The second calibration procedure utilized the method recommended by the gauge manufactured to calibrate the gauge for wet bulk density (eq. 2) along with an appropriate correction for the effect of water on gamma attenuation (eq. 3). The regression coefficients A and B in equation 2 were determined by utilizing a specially manufactured calibration stand consisting of slabs of materials of known density: polyethylene, magnesium, limestone, and aluminum. As a matter of practical expedience, periodic checks should be made to determine if the values of A and B are accurate; however, determination of the count rate in the reference scaling material (magnesium) should be done daily or more frequently. This procedure was referred to as the modified manufacturer's calibration (MM) method.

The final procedure was an attempt to calibrate the gauge by means of regression for each soil type investigated. Equation 4 was used for this purpose, where the values of C_3 and C_4 resulting in the best agreement between volumetric core bulk densities and that of the gamma gauge for each soil type and condition were determined. This was designated as the regression calibration (RC) method.

Results and Discussion

The comparison of dry soil bulk densities as determined by the use of volumetric cores versus gamma attenuation for the field sites located at Central City and Lexington, are shown in figures 1 and 2, respectively. Both figures indicate substantial random disagreement between the volumetric core and gamma gauge bulk densities. For the Central City site (fig. 1), the mean standard error of estimate was 0.162 $Mg \cdot m^{-3}$. The mean deviations corresponding to the MM, RC, and TC calibration methods were −2.1%, +3.2%, and +1.6%, respectively. The comparison of core versus gamma bulk densities at the Lexington site (natural soil) indicated slightly bener agreement than for the Central City site. The mean standard error of estimate was 0.083 $Mg \cdot m^{-3}$ or about half that of the reconstructed soil. The respective deviations for the MM, RC and TC gamma gauge calibration methods were −3.2%, 1.8% and −0.4%.

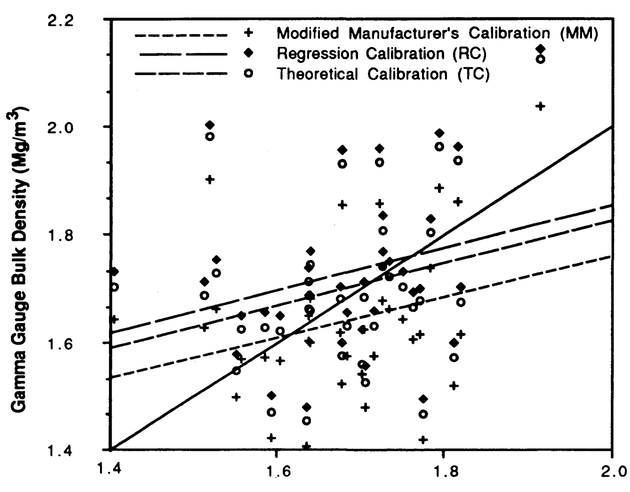

Figure 1–Comparison of core vs. gamma gauge bulk density using three calibration methods (Central City, Kentucky, site).

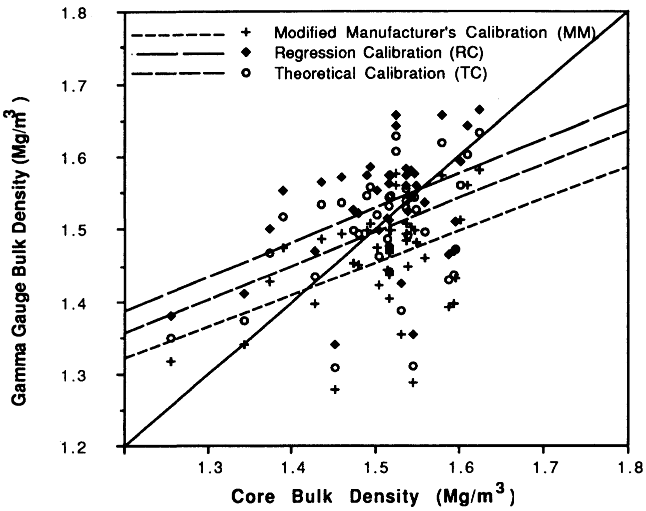

Figure 2–Comparison of core vs. gamma gauge bulk density using three calibration methods (Lexington, Kentucky, site).

Linear regression was used to determine the "best fit" relationships for gamma gauge versus core bulk densities in figures 1 and 2 and the corresponding regression parameters are given in Table 1. For both sites, the slopes of the regression lines of the various gamma gauge versus core density relationships were substantially less than one. Thus, there was a strong tendency in all situations for the gamma gauge to predict less than core density at relatively high density levels, while underpredicting at low levels.

There is no clear explanation for the degree of disagreement between gamma gauge and core bulk densities shown in figures 1 and 2. In a companion study (Luo and Wells, 1992) a similar comparison was made between gamma gauge densities and the average density of soil packed into a box of known volume. The corresponding slopes of the regression lines ranged from 0.871 to 1.008. We suspect, therefore, that additional error and uncertainty could be introduced by the extraction of cylindrical soil samples and the inaccurate location of parallel access holes. Instances of gamma gauge bulk density being less than core bulk density (below the diagonal lines on figs. 1 and 2) could result from: a) compression of soil during extraction of a core sample; and b) erroneous determination of gamma count due to less

TABLE 1. Linear regression parameters of core vs. gamma gauge soil bulk densities

	Central City Site		
	Manufacturer's Calibration	Theoretical Calibration	Regression Calibration
Slope	0.374	0.393	0.393
Intercept	1.013	1.042	1.068
R^2	0.077	0.074	0.077
	Lexington Site		
	Manufacturer's Calibration	Theoretical Calibration	Regression Calibration
Slope	0.440	0.461	0.472
Intercept	0.795	0.806	0.822
R^2	0.202	0.192	0.208

TABLE 2. Duncan's new multiple range analysis of mean soil bulk density measurements (g•cm^{-3})

	Gamma Gauge Calibration Method			
Soil	Core	Manufacturers'	Regression	Theoretical
Sadler silt loam	1.688 ab*	1.653 a	1.742 b	1.716 ab
Maury silt loam	1.509 a	1.459 b	1.535 a	1.501 a

* Within a soil type, values designated by same letter are not different at the 5% level of significance.

separation between the source and detector than 254 mm (10 in.). On the other hand, instances of gamma gauge bulk densities being greater than core bulk densities could be due to: a) loosening of soil core during extraction; or b) greater separation of gamma gauge source and detector than 254 mm (10 in.). Clearly the extremely low values of R^2 indicate that the linear model is an insufficient explanation of the relationship between core and gamma gauge bulk densities. The relatively large positive intercepts in Table 1 clearly suggest that extrapolation of the various linear relationships to bulk densities less than measured in this study would lead to erroneous results.

Analysis of variance revealed no significant different among soil bulk densities as determined by the various methods tested at the 5% level for the Sadler soil (Central City), whereas for the Maury soil (Lexington) a highly significant (<1%) difference was determined. The results of Duncan's new multiple range test (SAS, 1986) to determine potential differences between various methods tested are shown in Table 2. In the Sadler soil (Central City), only the RC and MM methods were significantly different and neither was significantly different from the core density. In the Maury soil (Lexington), only the MM calibration yielded a mean bulk density significantly different from the others, and it was only 3.3% less than the mean core bulk density. When both soils were combined, there was no significant difference between methods of determining soil bulk density. Using five soil types in this and a companion study (Luo and Wells, 1992), a composite analysis of data collected indicates a significant difference at the 5% level only between the regression and modified manufacturer's calibration methods. No calibration method was significantly different from core density. The mean errors associated with the regression (RC), theoretical (TC), and modified manufacturers (MM) calibration methods were, respectively, +2.15%, –1.13%, and –3.48%.

While the rate of emission of gamma photons is described by a random distribution, only a small degree of variation of gamma gauge bulk density ($\leq$0.01 Mg•m^{-3}) can be attributed to this variation. The results of this study indicate that for a single point of comparison, the difference between the methods of density measurement could be as great as 0.5 Mg•m^{-3}. However, the average deviation between methods was <3% when the manufacturer's calibration was followed and the effect of soil water on gamma attenuation was correctly considered. Thus, gamma attenuation can be used to determine an accurate survey of soil bulk density levels in the field and would certainly be more convenient than the use of volumetric cores when a substantial number of observations is desired. Also, there is no indication that a more

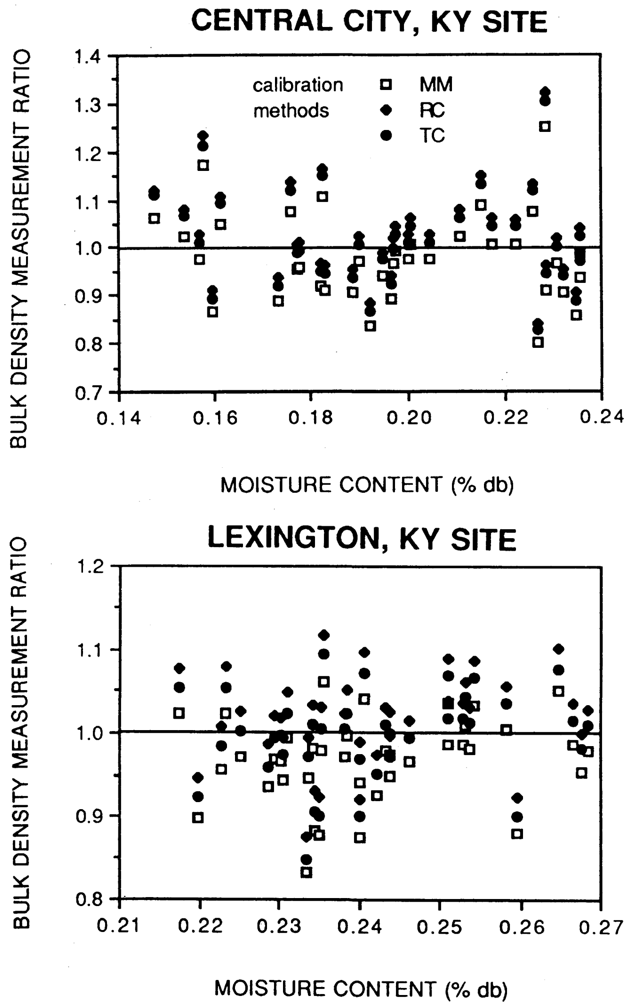

Figure 3–The effect of moisture content on bulk density measurement ratio (gamma gauge density/volumetric core density) for two field soils.

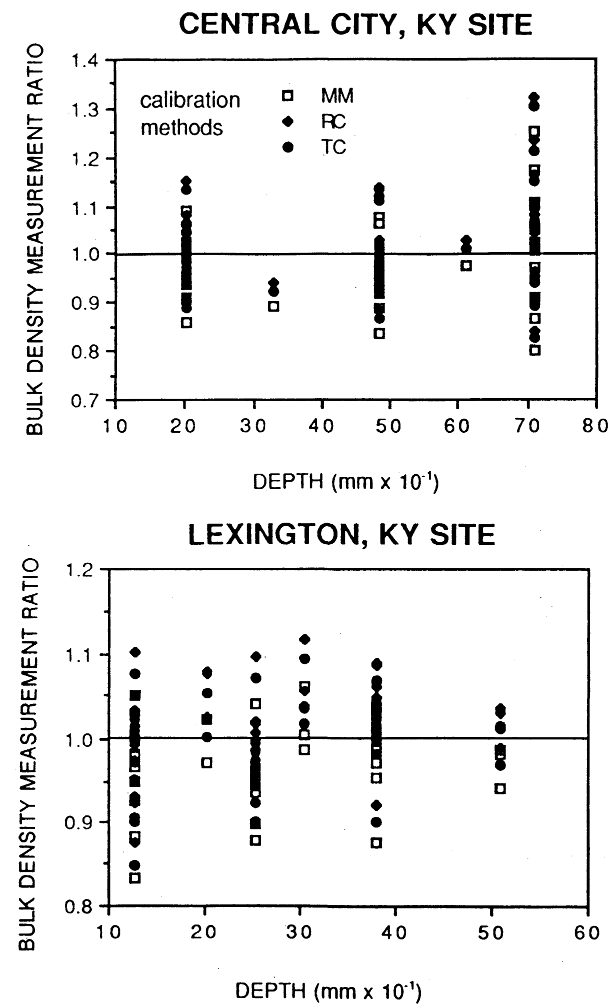

Figure 4–The effect of soil depth on bulk density measurement ratio (gamma gauge density/volumetric core density) for two field soils.

rigorous calibration of the gauge or empirical calibration for specific soil conditions is necessary or desirable.

Figure 3 indicates no discernable effect of soil moisture content upon the bulk density measurement ratio, i.e., the ratio of gamma gauge dry bulk density to that of volumetric cores. This was confirmed by Pearson correlation coefficients between moisture content and the deviation between dry core and gamma bulk densities corresponding to the MM, RC, and TC calibration methods of 0.0194, 0.0164, and 0.0484, respectively (SAS, 1986). Thus, there appears to be no moisture bias with regard to the comparison and we can conclude that any comparison of values is independent of soil moisture content.

Figure 4 shows no apparent effect of soil depth upon the agreement between the gamma gauge and volumetric cores. Linear regression analysis performed on the various data sets shown in figure 4 indicated a range of estimated slopes of 0.007 to 0.0034. The literature indicates that the transmission of gamma photons can be affected as source and detector near the soil surface, thereby indicating less than true bulk density. The safe depth for ignoring such an effect is generally given as approximately 100 mm (4 in.). All measurements in this study were taken at a soil depth greater than 100 mm (4 in.).

Finally, figure 5 indicates that equation 5 can be used to correct for erroneous determination of soil bulk density resulting from incorrect spacing of the source and detector. This is a welcome result given the difficulty of precise placement and alignment of the vertical access holes. Depending upon the accuracy requirement, equation 5 can

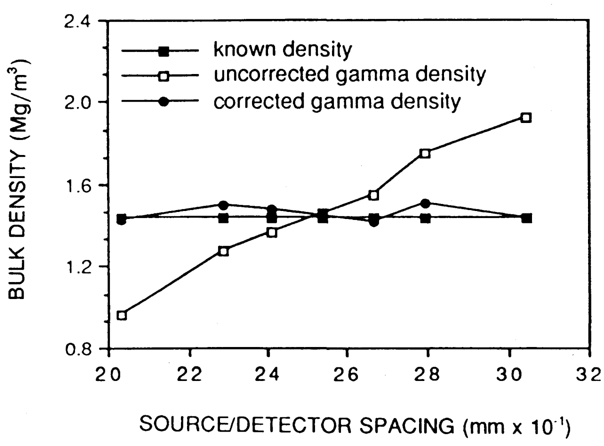

Figure 5–Comparison of corrected and uncorrected gamma gauge density vs. known density (Lexington, Kentucky, site).

be used to adjust gamma gauge density by direct or indirect determination of actual source-detector separation distance at any specific depth.

Conclusions

The conclusions of this study are as follows:

1. Gamma gauge bulk density may differ substantially (up to 10%) from that of volumetric core samples for a specific sampling location, however, the mean deviation of 288 measurements at the field sites was relatively small (≤±3%).
2. There was no discernable effect of soil water content upon the deviation between gamma gauge and volumetric core dry bulk density.
3. The ratio of gamma gauge and volumetric core bulk density decreased linearly with increasing soil density. The most likely explanation of this phenomena is density dependent alteration of true bulk density by the volumetric core samples.
4. There was no effect of soil depth upon the ratio of gamma gauge to volumetric core bulk density.
5. Potential error in gamma gauge bulk density resulting from incorrect source-to-source detector spacing can be corrected by a simple linear function of spacing deviation.

Finally, we have no reason to conclude that the gamma gauge is less accurate than volumetric core with respect to the determination of soil bulk density in the field. When properly used, the gamma gauge seems to be a preferable means of making numerous observations as well as monitoring changes over time of soil bulk density at specific locations.

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